The carbon footprint of household energy use in the United States

Benjamin Goldstein[a,1], **Dimitrios Gounaridis**[a], **and Joshua P. Newell**[a]

[a]School for Environment and Sustainability, University of Michigan, Ann Arbor, MI 48109

Edited by M. Granger Morgan, Carnegie Mellon University, Pittsburgh, PA, and approved June 4, 2020 (received for review December 18, 2019)

Residential energy use accounts for roughly 20% of greenhouse gas (GHG) emissions in the United States. Using data on 93 million individual households, we estimate these GHGs across the contiguous United States and clarify the respective influence of climate, affluence, energy infrastructure, urban form, and building attributes (age, housing type, heating fuel) in driving these emissions. A ranking by state reveals that GHGs (per unit floor space) are lowest in Western US states and highest in Central states. Wealthier Americans have per capita footprints ∼25% higher than those of lower-income residents, primarily due to larger homes. In especially affluent suburbs, these emissions can be 15 times higher than nearby neighborhoods. If the electrical grid is decarbonized, then the residential housing sector can meet the 28% emission reduction target for 2025 under the Paris Agreement. However, grid decarbonization will be insufficient to meet the 80% emissions reduction target for 2050 due to a growing housing stock and continued use of fossil fuels (natural gas, propane, and fuel oil) in homes. Meeting this target will also require deep energy retrofits and transitioning to distributed low-carbon energy sources, as well as reducing per capita floor space and zoning denser settlement patterns.

sustainability | climate change | built environment | energy | cities

Roughly 20% of US energy-related greenhouse gas (GHG) emissions stem from heating, cooling, and powering households (1). If considered a country, these emissions would be considered the world's sixth largest GHG emitter, comparable to Brazil and larger than Germany (2). By 2050, the United States will add an estimated 70–129 million residents (3) and 62–105 million new homes (4). Although houses are becoming more energy efficient, US household energy use and related GHG emissions are not shrinking due to demographic trends, expanding use of information technologies, electricity prices, and other demand drivers (5, 6).

This lack of progress undermines the substantial emission reductions needed to mitigate climate change (7). The average lifespan of an American home is about 40 y (8), which poses challenges given the need to rapidly decarbonize. This makes decisions during design and construction, such as size, heating systems, building materials, and housing type, crucial. In the United States, a confluence of post-World War 2 policies helped move a majority of the population into sprawling, suburban households (9, 10) with energy consumption and attendant GHGs well above the global average (11). Without decisive action, there will be a "carbon lock-in" for these homes for decades to come (12, 13).

Despite the urgency, fundamental questions remain unanswered. Researchers have lacked the nationwide building-level data necessary to identify the states with the most energy and carbon intensive housing stocks. Given their autonomy in developing energy policies and building codes, state and local governments would find this especially useful. How household energy emissions vary across income groups is not well understood but important given the rapidly changing demographics of US cities and suburbs (14). Research has traditionally focused on geographically limited cases (15–17) or lumped building energy emission with other end uses in carbon accounting (18, 19). Finally, the influence of built form—the spatial relationships between buildings—and emissions have only been explored for a few US cities (20, 21).

The incomplete diagnosis of the drivers of emissions hampers our understanding of the needed transformations to tackle carbon lock-in. Can low-density communities across the United States meet long-term climate mitigation goals for building energy use if the electrical grid decarbonizes? If not, what additional measures (e.g., energy retrofits and substitution of in-home fossil fuels) will be necessary? Will future low-carbon communities have to consist of smaller homes built in high-density settlements?

To answer these questions, we used data at the building level to estimate the residential GHG emissions of ∼93 million homes in the contiguous United States (78% of the national total). Using household-level information on building age, enclosed area, housing type, and heating fuels, we evaluated the influence of climate, income, building form, and electrical grid at multiple scales using regression models derived from national energy statistics. We then modeled four scenarios to test if various technology transitions could achieve the Paris Agreement 2025 and 2050 targets.

We find that both household energy use and emissions per square meter vary widely across the country, driven primarily by thermal energy demand and the fuel used in electricity production ("grid mix"). ZIP-code level analysis shows income is positively correlated with both per capita energy use and emissions, along with the tendency for wealth and living area to increase together. City and neighborhood analyses underscore the environmental benefits of denser settlement patterns and the degree

Significance

This study uses data on ∼93 million individual homes to perform the most comprehensive study of greenhouse gases from residential energy use in the United States. We provide nationwide rankings of carbon intensity of homes in states and ZIP codes and offer correlations between affluence, floor space, and emissions. Scenarios demonstrate this sector cannot achieve the Paris Agreement 2050 target by decarbonizing electricity production alone. Meeting this target will also necessitate a broad portfolio of zero emission energy solutions and behavioral change associated with housing preferences. To support policy, we estimate the reductions in floor space and increases in density needed to build low-carbon communities.

Author contributions: B.G., D.G., and J.P.N. designed research; B.G. performed research; B.G., D.G., and J.P.N. analyzed data; B.G. and J.P.N. wrote the paper; and B.G. and D.G. produced graphics.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

Data deposition: The data and code that support the findings of this study are available on the Open Science Framework platform (DOI: 10.17605/OSF.IO/VH4YJ), with the exception of CoreLogic data, which are available for purchase from CoreLogic Inc. (https://www.corelogic.com/).

[1]To whom correspondence may be addressed. Email: benjgo@umich.edu.

This article contains supporting information online at https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.1922205117/-/DCSupplemental.

SUSTAINABILITY SCIENCE

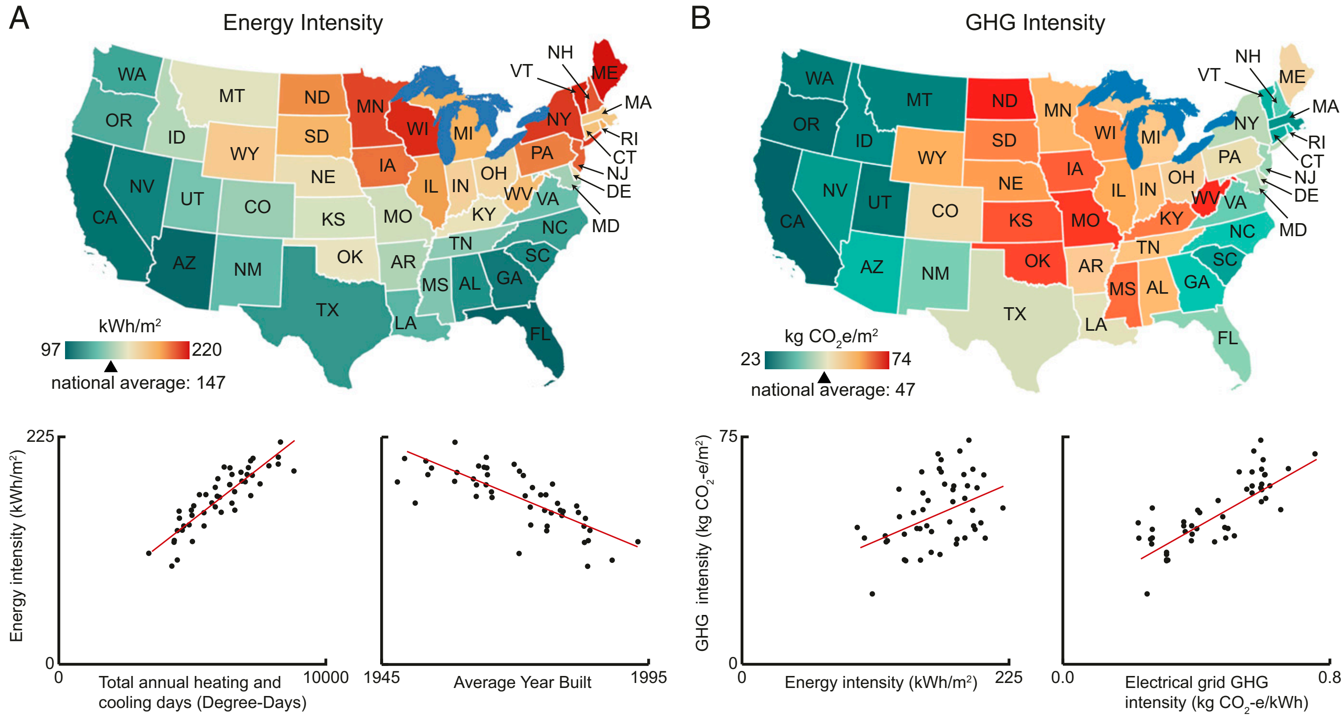

Fig. 1. Energy and GHG intensity of homes in 2015 by US state. (*A*) Household energy intensity represented by kilowatt-hours per square meter (kWh/m^2) by state (*Upper*). (*Lower*) Scatterplots show energy intensity correlations with annual sum of daily average deviation from ∼18 °C (65 °F), degree days (*Left*) (n = 49, P value = 4.4 e-16, r = 0.87), and average year built (*Right*) (n = 49, P < 5.6 e-10, r = −0.75). (*B*) Household GHG intensity represented by kilograms CO_2-equivalents per square meter (kg CO_2-e/m^2) by state (*Upper*). Scatterplots showing its correlations with household energy intensity (*Left*) (n = 49, P = 0.002, r = 0.43) and carbon intensity of the electrical grid (*Right*) (n = 49, P = 5.2 e-12, r = 0.80).

to which carbon-intensive electrical grids counteract these benefits.

Residential energy emissions arise from a combination of economic, urban design, and infrastructural forces. Our exploratory scenario-based models indicate that meaningful reductions to residential emissions will require concurrent grid decarbonization, energy retrofits, and reduced in-home fuel use. Scenarios also suggest that making new construction low-carbon will require smaller homes, which can be promoted through denser settlement patterns. These results have implications for both the United States and other nations.

Results

Energy and GHG Intensity of States. Existing literature has explored residential energy use per capita and per household across the United States (22, 23). However, it has not been clear whether efficiency stems from the number of people per household, floor space, building attributes, or other factors. We use large samples of each state's housing stock ($n \sim 10^5$ to 10^7) to estimate the energy use and related GHG emissions per square meter of dwelling across the contiguous United States (herein, "energy intensity" and "GHG intensity"). In our analysis, a "home" can be a building containing only one household (detached single-family households and mobile homes) or an individual unit in a building containing multiple households (apartment buildings, semidetached homes/duplexes, townhomes). Intensity metrics provide a clear picture of the performance of each state's housing stock, irrespective of demographic variation and home size preferences. We find that climate and, to a lesser degree, building age covary with energy intensity, whereas energy infrastructure strongly influences GHG intensity (Fig. 1 *A* and *B*).

Based on our models, the average US home consumed 147 kilowatt-hours per square meter (kWh/m^2) in 2015, consistent with 143–175 kWh/m^2 from national residential energy statistics (24). Estimates of individual states agree with building energy surveys and engineering models (*SI Appendix*, Table SI-25). Climate, as measured by the annual sum of daily average deviation from ∼18 °C (65 °F) ("degree-days"), tightly correlates with household energy intensity (r = 0.87) (Fig. 1 *A*, *Lower Left*). This is consistent with thermal conditioning representing the largest share of household energy consumption in the United States (25) and other nationwide analyses (22, 23). States in warm or mild regions have low energy intensity, whereas the energy intensity in cold north-central and northeast states is markedly higher (Fig. 1 *A*, *Upper* and *SI Appendix*, Table SI-30). The three most energy intensive states in 2015 have some of the highest number of degree-days: Maine, Vermont, and Wisconsin. The three least, Florida, Arizona, and California, have some of the lowest degree-days.

Given the ongoing adoption of residential energy codes (26, 27), which establish baseline requirements for energy efficiency of homes, we predict that states with newer housing stocks would use less energy. Indeed, average year of building construction negatively correlates with energy intensity (r = −0.80) (Fig. 1 *A*, *Lower Right*), which aligns with observations from national statistics (*SI Appendix*, Table SI-29). The relationship between building age and energy intensity is attenuated by design preferences that increase energy consumption in newer homes, such as higher ceilings (28).

We estimate average US emissions of GHG intensity as 45 kg of CO_2-equivalents per square meter (CO_2-e/m^2), nearly identical to national energy accounts (47 kg CO_2-e/m^2) (*SI Appendix*, Table SI-26). Although GHG intensity and energy intensity are positively correlated (r = 0.43), there is substantial variation between them among some states (Fig. 1 *B*, *Lower Left*). Comparing Fig. 1 *A* and *B* shows that energy and GHG intensity align

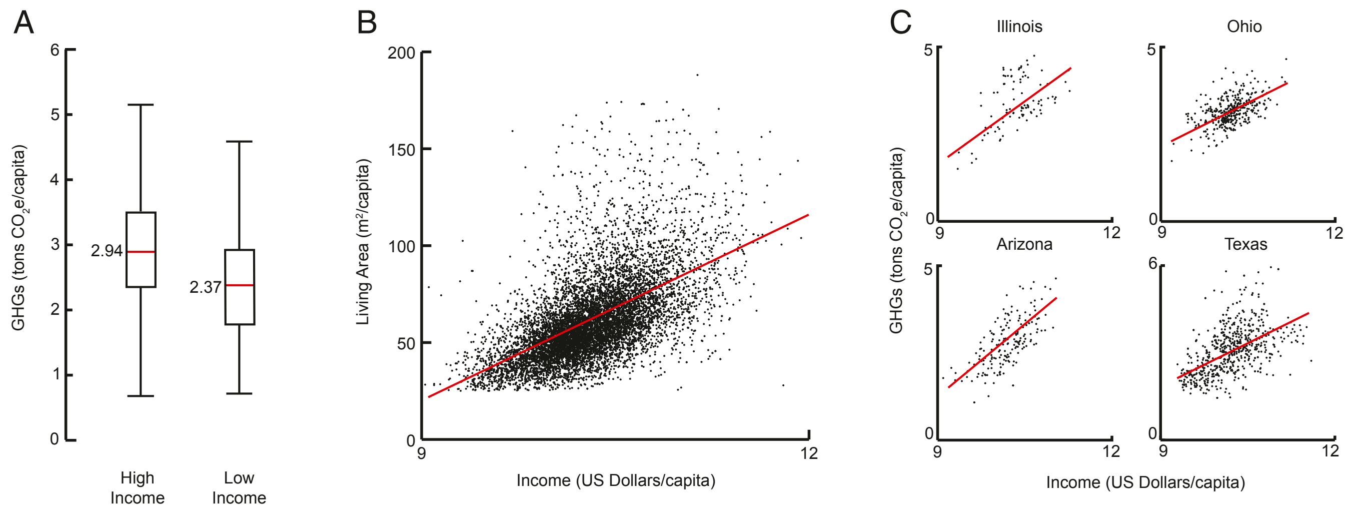

Fig. 2. Influence of income on living area and household energy emissions. (*A*) Boxplots of per capita emissions of households classified as high income (n = 7,141) or low income (n = 1,717) according to the US Department of Housing and Urban Development's 2015 poverty thresholds. Outliers not shown but included in calculation of averages (red lines). (95% C.I.: 0.52–0.62, $P < 2.2$ e-16, t test) (*B*) Scatterplot of per capita income against per capita living area. Income is plotted on natural logarithmic axes (n = 8,858, $P < 2.2$ e-16, r = 0.57). (*C*) Scatterplots of per capita income against per capita emissions for Illinois (*Upper Left*) (n = 101, P = 3.05 e-10, r = 0.58), Ohio (*Upper Right*) (n = 364, $P < 2.2$ e-16, r = 0.58), Arizona (*Lower Left*) (n = 178, $P < 2.2$ e-16, r = 0.72), and Texas (n = 574, $P < 2.2$ e-16, r = 0.55).

in some western and north-central states, such as California (low kWh/m^2, low kg CO_2-e/m^2) and Illinois (high kWh/m^2, high kg CO_2-e/m^2), but that these measures are not aligned in other states, such as Missouri (medium kWh/m^2, very high kg CO_2-e/m^2) and Vermont (very high kWh/m^2, medium kg CO_2-e/m^2) (*SI Appendix*, Table SI-30).

A strong correlation between the carbon intensity of the electrical grid supplying a state and its household GHG intensity (r = 0.80) may account for these anomalies (Fig. 1 *B*, *Lower Right*). GHG-intensive electricity production can erase the benefits of low household energy intensity. For example, Florida has low energy intensity (97 kWh/m^2) but an intermediate GHG intensity (45 kg CO_2-e/m^2). In Missouri, an average household energy intensity (165 kWh/m^2) combines with the high carbon intensity of the Midcontinent Independent System Operator Central grid (0.74 kg CO_2-e/kWh compared to 0.48 kg CO_2-e/kWh nationally) to produce some of the most GHG-intensive households (69 kg CO_2-e/m^2) in the country. States with extensive use of carbon-intensive heating fuels, such as Maine with ~2/3 of households heated with fuel oil (29), diminish the benefits of low-carbon grids.

Per Capita Emissions across the United States. Samples of building stocks at the state-level are suitable for estimating energy and carbon intensity, but large aggregate data obscure heterogeneity in affluence, housing stocks, and settlement forms. To understand links between income, building characteristics, population density (persons/km^2) and individual GHG burdens, we estimated per capita household energy emissions for 8,858 ZIP codes across the contiguous United States.

Residential energy use in the United States produces 2.83 ± 1.0 t of CO_2-equivalents per capita (t CO_2-e/cap), consistent with 3.19 t CO_2-e/cap estimated from national energy statistics (1) (*SI Appendix*, Table SI-27). Across the ZIP codes, per capita GHG emissions range from 0.4 t CO_2-e/cap to 10.8 t CO_2-e/cap with an interquartile range of 1.2 t CO_2-e/cap (*SI Appendix*, Fig. SI-5).

We compare GHG emissions for high-income and low-income ZIP codes, using the federal poverty thresholds (30). High-income residents emit an average of ~25% more GHGs than low-income residents (Fig. 2*A*). In energy models, consumption side accounting has found similar links using energy expenditure data (19) and using income as an explanatory variable (18). The building-level data enabled the capture of housing attributes afforded by affluence—greater floor space, access to older, established neighborhoods—while keeping income endogenous to our model. We find a strong positive correlation (0.57) between per capita income and floor area per capita (FAC) (m^2/cap) (Fig. 2*B*). The tendency for affluence and FAC to increase together is a key emissions driver for wealthier households. Despite variations in climates, grid mixes, and building characteristics across our sample, income positively correlates with both per capita residential energy use (r = 0.33) and related GHGs (r = 0.16) (*SI Appendix*, Fig. SI-6). Analysis by state—which partially controls for variation in climate, grid, and building stock—strengthens this correlation as illustrated by all 48 states (*SI Appendix*, Table SI-31) and four representative ones (Fig. 2*C*).

There is ample literature demonstrating the building energy and related carbon benefits of high population density (18, 31, 32). Our results also highlight the influence of density on floor space and residential energy GHG emissions. For all ZIP codes (*SI Appendix*, Fig. SI-7) and in most states, increasing population density associates with decreased FAC and GHG intensity (*SI Appendix*, Table SI-31). Population density (persons/km^2) negatively correlates with both FAC (r = −0.19) and GHG emissions per capita (r = −0.29) across all ZIP codes. Our analysis confirms the FAC–density relationship and its impacts on energy noted using regional data (33). Variation in GHG intensity among the ZIP codes likely reflects differences in climate, building characteristics, and carbon intensity of the electrical grid, such that the overall relationship between density and emissions is attenuated. Analyzing individual states illustrates the strength of the density–GHG relationship, as represented by Illinois (r = −0.76), California (r = −0.52), and Georgia (r = −0.44). A notable exception is New York (r = 0.50), which has a positive correlation between density and GHG intensity, likely because Greater New York City has a carbon-intensive electrical grid (34).

Income, Built Form, and Emissions across Cities. Although the ZIP code-level results show that density and FAC influence per capita GHG emissions, they do not indicate how these vary spatially

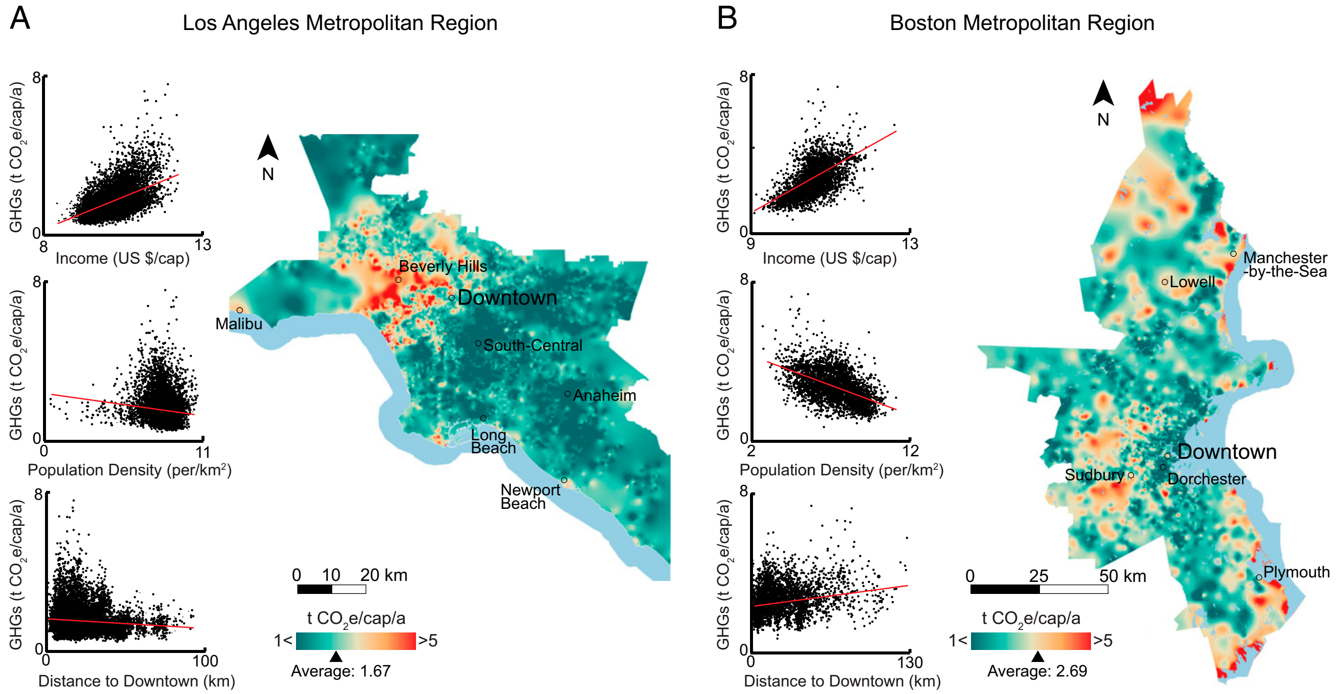

Fig. 3. Carbon footprints from household energy use in Los Angeles and Boston. (*A*) Map of per capita emissions across Los Angeles. Scatterplots show relationships between per capita emissions and income (*Upper*) (n = 6,800, P < 2.2 e-16, r = 0.55), density (*Middle*) (n = 6,800, P < 2.2 e-16, r = −0.15) and distance from downtown (*Lower*) (n = 6,800, P < 2.2 e-16, r = −0.16). (*B*) Map of per capita emissions across Boston. Scatterplots show relationships between per capita emissions and income (*Upper*) (n = 3,079, P < 2.2 e-16, r = 0.54), density (*Middle*) (n = 3,079, P < 2.2 e-16, r = −0.49) and distance from downtown (*Lower*) (n = 3,079, P < 2.2 e-16, r = 0.20). Income and density are plotted on natural logarithmic axes. Diameter of circle graph is proportional to total emissions.

within US cities, which is where roughly 80% of Americans live (35). Moreover, density does not constitute urban form (33), which makes it difficult to ascertain what low-carbon neighborhoods look like (e.g., high-rises, townhomes) with this measure alone. We spatialize our results for two cities to see how the interplay of income, built form, and energy infrastructure distribute emissions across urban landscapes. We focus on two large Metropolitan Statistical Areas (MSAs) that in many ways are opposing archetypes of many US cities. Boston-Cambridge-Quincy (2015 population: 4,694,565) has a cold climate, displays a monocentric urban form, and is composed of mostly old building stock. Los Angeles-Long Beach-Anaheim (2015 population: 13,154,457) (8) is in a mild climate with a polycentric layout and newer housing stock (post-1950).

Our model estimates per capita emissions as 1.67 t CO_2-e/cap/a in Los Angeles and 2.69 t CO_2-e/cap/a in Boston. Analysis of census "block groups" (~1,500 residents), a proxy for neighborhoods, reveals substantial inner-city variation. To start, we focus on block groups with very high and very low per capita emissions to isolate the forces driving emissions (*SI Appendix*, Table SI-32).

High-emissions neighborhoods are primarily high income or extremely high income. In contrast, for both cities, 14 of the 20 neighborhoods with the lowest emissions fall below the poverty threshold. The difference in emissions between nearby high- and low-income neighborhoods sometimes approaches a factor of 15. For both cities, we find much greater FAC and lower population densities in the neighborhoods with the highest emissions. Contrasting GHGs in affluent Beverly Hills, Los Angeles, and Sudbury, MA, with low-income South-Central, Los Angeles, and Dorchester, Boston, spotlights the influence of built form (*SI Appendix*, Fig. SI-8). Both Beverly Hills and Sudbury are areas of suburban sprawl: very large detached homes isolated on large plots. Beverly Hills displays a high building footprint ratio, which is often associated with higher density and lower GHGs (32), but homes are so large that per capita emissions are greater than those in Sudbury despite the favorable climate and less carbon-intensive grid. Dorchester and South-Central Los Angeles are decidedly urban: small plots, uniform buildings, and high building footprint ratio. The built form is predominantly detached and semidetached households, with some units split into apartments with low FAC. Low-carbon neighborhoods, thus, need not be uninterrupted blocks of apartments like many of the low-emissions neighborhoods in Boston.

The two MSAs exhibit varied spatial distribution of per capita emissions (Fig. 3 *A* and *B*). Despite the polycentric urban form, per capita emissions in Los Angeles are monocentric in space with the highest emissions on the mountainous west side of Los Angeles (Fig. 3 *A*, *Right*). This area contains all 10 neighborhoods with the highest per capita GHG emissions. Others have identified a general tendency for higher emissions in the suburbs compared to US inner cities (18). The negative correlation between per capita emissions and distance to downtown (Fig. 3 *A*, *Lower Left*) shows that this may not hold for postmodern cities like Los Angeles. A relatively even population distribution plays a role (Fig. 3 *A*, *Middle Left*), but more important is the high percentage of coal in the electrical grid supplying the city compared to coal use for electricity in outlying areas of the MSA (37% vs. 6%) (36). In the Boston MSA, per capita emissions are higher in the suburbs than in the city proper (Fig. 3 *B*, *Right*). These emissions increase more consistently with distance from city center than in Los Angeles (Fig. 3 *B*, *Lower Left*). This distribution of per capita emissions is consistent with a classic monocentric urban form of dense core surrounded by sprawling suburbs.

The negative correlation between population density and per capita emissions is stronger in the Boston MSA ($r = -0.49$) than in the Los Angeles MSA ($r = -0.16$). The high carbon intensity of the energy grid supplying central Los Angeles counteracts the energy benefits of a compact urban form (18, 37). For instance, per capita emissions in South-Central Los Angeles are double

Table 1. **Four decarbonization scenarios: The scenarios model pathways for GHG emissions reductions for existing US households to 2050**

Scenario	Electrical grid	Energy retrofit rate (annual %)	Efficiencies of appliances, home electronics, heating and cooling equipment	Distributed low-carbon energy
1. Baseline	Energy Information Administration (EIA) projection to 2050 (current trends)	1.1	Average	Minor contributions to grid
2. Aggressive Energy Retrofits	EIA projection to 2050 (current trends)	1.7	High	Minor contributions to grid
3. Grid Decarbonization with Aggressive Energy Retrofits	EIA projection to 2050 (current trends)	1.7	High	Minor contributions to grid
4. Distributed Low-Carbon Energy	80% decarbonization relative to 2005	1.7	High + additional heat pumps	Household solar water and photovoltaics; local combined heat and power

those of the low-carbon neighborhoods in the MSA, despite a similar FAC and built form (*SI Appendix*, Table SI-32). The energy savings and lower per capita emissions in the dense City of Boston are more apparent because differences in the carbon intensity of the energy grid between the city and the suburbs are less pronounced than in Los Angeles.

In the Los Angeles MSA, income correlates positively with per capita emissions ($r = 0.55$) (Fig. 3 *A*, *Upper Left*) and FAC ($r = 0.59$) (*SI Appendix*, Fig. SI-9). We find a similar relationship between income and per capita emissions ($r = 0.54$) (Fig. 3 *B*, *Upper Left*), but a slightly weaker relationship with FAC ($r = 0.41$) (*SI Appendix*, Fig. SI-9) in Boston MSA. Wealthy enclaves of dense apartment blocks, such as Beacon Hill and Back Bay, adjacent to Boston's downtown effect this correlation. The low-carbon electrical utilities owned by some affluent suburbs dampen the income–emissions relationship (38).

Discussion

Results suggest two practical interventions to mitigate GHGs from residential energy: 1) reducing fossil use in homes and in electricity generation (decarbonization) and 2) using home retrofits to cut energy demand and in-home fuel use. We model four scenarios (Baseline; Aggressive Energy Retrofits; Grid Decarbonization with Aggressive Energy Retrofits; and Distributed Low-Carbon Energy) to see if these measures would enable existing homes in the Boston and Los Angeles and the United States as a whole to reach the Paris Agreement targets, which call for a reduction of emissions from 2005 levels by 28% in 2025 and 80% in 2050 (39).

Scenario 1, Baseline, follows trends outlined in the US Energy Information Administration (EIA) 2020 Annual Energy Outlook (5, 40, 41). Scenario 2, Aggressive Energy Retrofits, assumes deeper home energy retrofits happening at an accelerated rate. Scenario 3, Grid Decarbonization with Aggressive Energy Retrofits, complements retrofits with 80% electrical grid decarbonization. Scenario 4, Distributed Low-Carbon Energy, sees increased diffusion of low-carbon energy sources. Table 1 specifies the details of these four scenarios and *SI Appendix* 1 provides full descriptions.

Scenario 1 shows that the United States (ZIP-code level) can meet the Paris 2025 goal given current trends (Fig. 4*A*). This scenario seems plausible given that the carbon intensity of electrical

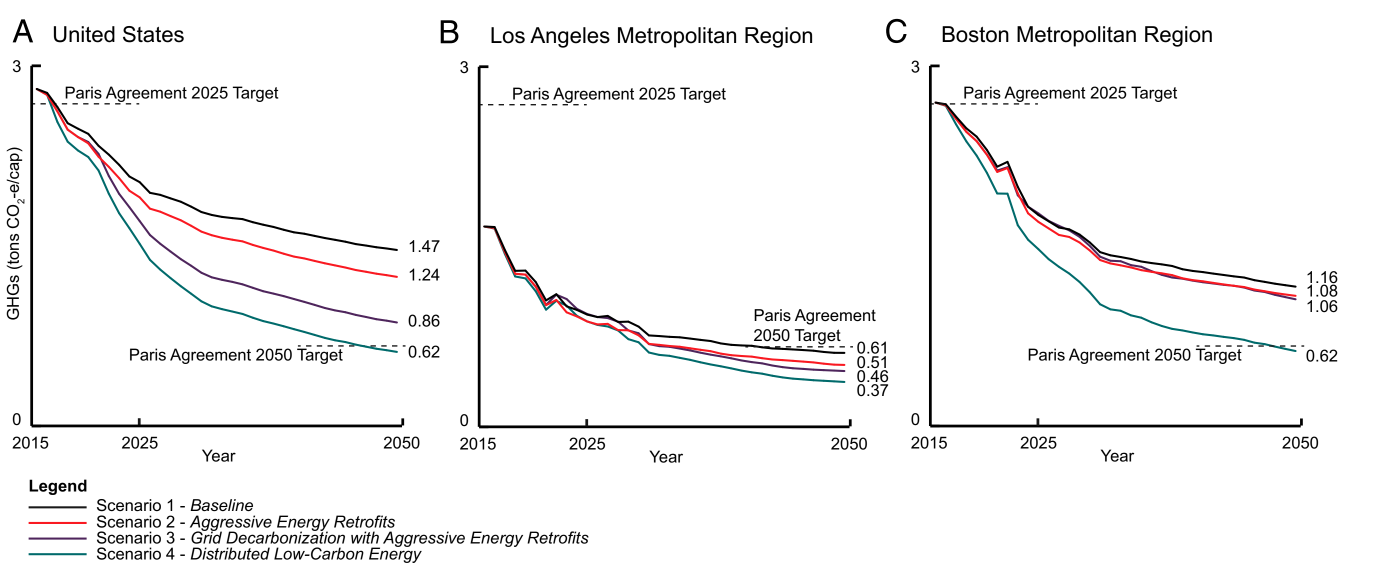

Fig. 4. Pathways to the Paris Agreement targets in 2025 and 2050 for residential energy use. Scenarios 1–4 for decarbonization of the electrical grid, home energy retrofits, and addressing in-home fuel use. Scenario 1: reference scenario of projected grid decarbonization and home retrofit rates according to the US Energy Information Administration. Scenario 2: aggressive energy retrofits of households. Scenario 3: aggressive home energy retrofits and grid decarbonization. Scenario 4: grid decarbonization, aggressive home energy retrofits, and distributed low-carbon energy. Results are for 8,588 ZIP codes in the United States (*A*), 3,079 block groups in Boston (*B*), and 6,800 block groups in Los Angeles (*C*).

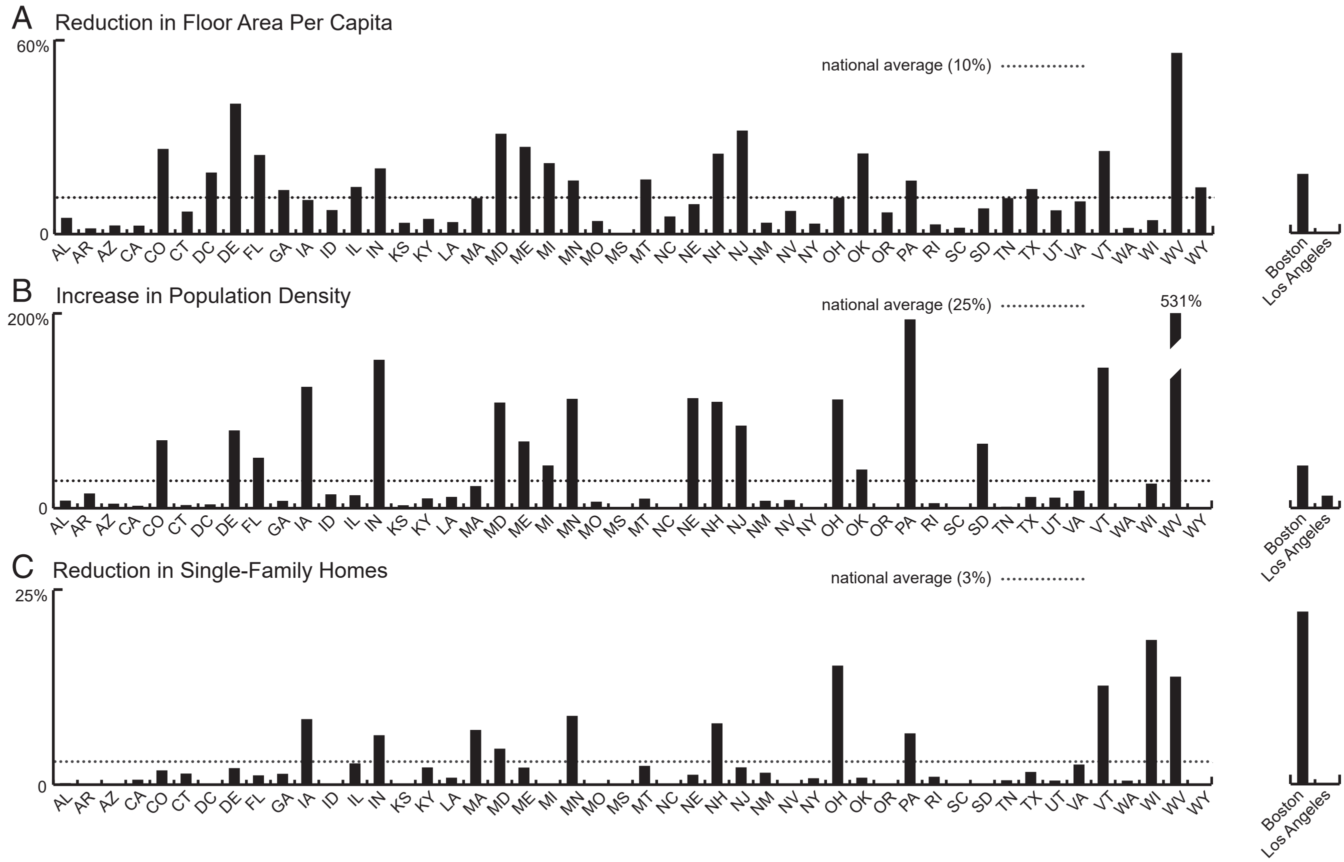

Fig. 5. Built form and the Paris Agreement 2050 target. Attributes of neighborhoods meeting the Paris Agreement target in scenario 4 relative to the 2015 average in each state and two case cities for FAC (*A*), population density (persons/km^2) (*B*), and percentage of single-family homes (*C*). Nonvalues indicate no difference between communities meeting the 2050 Paris target in scenario 4 and 2015 average. North Dakota not shown, since it lacked communities that met 2050 Paris target. Results for all scenarios in *SI Appendix*, Tables SI-30–32.

utilities dropped ~17% nationally between 2005 and 2015 (*SI Appendix*, Table SI-22). The United States is unlikely to meet the 2050 goal, even with aggressive home retrofits and grid decarbonization, due to continued in-home fossil fuel use. Scenario 4 shows how a multipronged strategy overcomes this. Natural gas furnaces and electric resistance systems still heat half of US homes, but heat pumps are deployed at three times the rate of scenario 1, cutting electricity use and displacing fuels. Distributed, low-carbon energy production in the form of combined heat and power (CHP) using a mix of fossil and carbon-neutral fuels, photovoltaics, and solar water heaters are prominent, with ~40% of homes using at least one of these technologies (*SI Appendix*, Table SI-24).

Per capita emissions in Los Angeles already fall below the Paris 2025 goal (Fig. 4*B*). The city meets the 2050 Paris target in scenario 1 because of its low baseline energy demand and significant grid decarbonization. Deeper decarbonization and more aggressive retrofits reduce emissions to nearly half the Paris goal in scenario 4. While Boston achieves the 2025 target in scenario 1, high baseline energy demand and continued in-home fuel use keep the city from meeting the 2050 goal despite substantial grid decarbonization (Fig. 4*C*). Additional grid decarbonization and aggressive retrofits do not overcome this shortfall in scenarios 2 and 3. In scenario 4, Boston meets the 2050 goal with heat pumps in 30% of homes and by using distributed low-carbon energy sources in 40% of homes.

Our scenario results indicate that deep cuts in emissions from the residential sector are achievable across the United States by combining production-side and consumption-side strategies. On the production side, decarbonization of electrical grids is the most important. Current projections foresee a continued substitution of coal with natural gas (26). More complete decarbonization is needed for the residential sector to meet the Paris goals. For example, in scenario 4 and relative to the 2050 reference scenario, the grid includes an 86% reduction in coal use and a 60% increase in renewables. Systems that provide CHP can completement some of these shifts in the mix of bulk generation. In scenario 4, the use of cogeneration is doubled (42). Consumption-side strategies include "deep" energy retrofits to reduce heating, cooling, and lighting loads. Individual homes can also source low-carbon energy. We included on-site solar panels or water heaters on one-third of homes in scenario 4. These systems necessitate on-site energy storage and connections to the grid to maximize their effectiveness.

Upgrading windows and installing heat pumps and solar systems requires investment by homeowners. The positive relationship between income and emissions suggests that Americans with the highest emissions are also best situated economically to bear these costs. Reducing the carbon footprint of US homes provides opportunities to combat energy poverty (43). For an estimated 25 million US households annually, energy bills supplant the purchase of food and medicine (24). Retrofitting homes in low-income neighborhoods, with financial support from government, perhaps funded through carbon levies on select industries, could cut emissions and energy bills. While high rental rates in low-income neighborhoods and the related misalignment between tenant and landlord interests hinder energy renovations (44), the technical potential is high. For example, rooftop photovoltaics are a suitable technology for more than half of residential buildings in low-income neighborhoods in the United States (45).

New homes need energy saving (e.g., low emissivity windows, insulated concrete forms) and low-energy heating and cooling technologies, as well as on-site low-carbon sources wherever possible. Meeting the 2050 Paris target also requires fundamental changes to the built form of communities. New homes will need to be smaller, with FAC in ZIP codes meeting the 2050 target in scenario 4 being 10% lower than the current average (Fig. 5*A* and *SI Appendix*, Table SI-33). FAC reductions are even greater in some states where significant population growth is expected, like Colorado (26% reduction), Florida (24% reduction), Georgia (13% reduction), and Texas (14% reduction). Although reductions appear drastic in some states, FAC in these smaller homes is similar to that of other wealthy countries (22).

Increasing population density places downward pressure on FAC due to space constraints, land prices, and other factors. Zoning for denser settlement patterns better incentivizes smaller homes with reduced energy demands than single-family homes on large lots. Neighborhoods meeting the Paris 2050 goal were 53% denser in Boston MSA than 2015 averages (Fig. 5*B* and *SI Appendix*, Table SI-34). This corresponds to ∼5,000 residents/km^2, a critical threshold for home energy efficiency in US communities (31). If built using small plots and high building footprint ratio, this density is achievable through a mix of small apartment buildings and modest single-family homes (e.g., *SI Appendix*, Fig. SI-8, *Bottom*). Nationally, density needs to increase on average by 19% with significant variation between states. Although modest, it does require building fewer single-family homes (Fig. 5*C* and *SI Appendix*, Table SI-35). In scenarios 1–3, more substantial changes to FAC and built form are foreseen.

Of note is that even the highest estimated densities fall at the low end of the spectrum of what is considered viable to support public transit (4). Thus, low-carbon homes do not necessarily make for low-carbon communities. Higher densities (and mixed-use development) are likely needed to confer appreciable spillover effects, such as increased low-carbon transport (18, 32, 46) and related economic, health, and social benefits (32, 33).

Implementing these strategies needs to take place across sectors and scales. Decarbonizing the power sector requires regional coordination. Deep home energy retrofits are likely to require tax incentives and preferential lending mechanisms. The Northeast United States provides an example of policy coordination, with a regional GHG cap and trade system driving grid decarbonization (47) and tax breaks incentivizing homeowners to phase out fuel oils (48). Updating federal loan practices and municipal zoning that have long favored suburban expansion (9) and using regional greenbelts to limit urban sprawl (49) can promote building low-carbon communities. Planners should exploit natural synergies between density, public transport, and energy infrastructure (e.g., district heating) when building these communities.

All these measures need to happen in concert. Although ambitious, the form of the current US housing stock is not only the outcome of consumer preferences, but also policies enacted since the 1950s that led to coordinated action across sectors (e.g., financial, construction, transport) and scales (individual, municipal, state, and national) (9). Similarly, a burst of large-scale projects by the Public Works Association (e.g., Hoover Dam) as part of the New Deal in the 1930s and 1940s fundamentally shaped the structure of US power sector. Given this history, it is conceivable that a concentrated effort could enable the US residential sector to meet Paris Agreement targets.

Materials and Methods

Data Preparation. Building-level data were from CoreLogic (50), a database of standardized tax assessor records of ∼150 million US land parcels. We used an early 2016 version of the data covering the US building stock in 2015. These data contain information key to estimating energy consumption of each household: building latitude and longitude, construction year, land use, housing type (detached, semidetached, apartment, mobile home), thermally conditioned floor area (herein "area"), number of apartments, and heating fuels. Heating fuels describes 35 common heating systems and fuel combinations (see *SI Appendix*, Table SI-5). We used data for 92,620,556 US households across the contiguous United States (excluding Alaska, Hawaii, and US territories), equivalent to 78.4% of total estimated US housing units in 2015 (24).

CoreLogic data contain residential, commercial, manufacturing, and other building types. We isolated residential buildings using land use and building type as filters (see *SI Appendix*, Table SI-1). We excluded institutional dwellings (e.g., dorms, prisons) as they are not representative of where most Americans live and are transitional living situations. We removed entries lacking year built, location, or area. We also removed entries with unreasonably large or small areas given US housing characteristics (see *SI Appendix*, Fig. SI-1 and Table SI-2). We checked data on apartment buildings to ensure that the number of apartments, area per apartment, and total building area agreed and fell within reasonable bounds. We occasionally estimated the number of apartments in a building, which increased the initial 83,317,764 usable entries to 92,620,556. We filled missing space heating fuels using data from the American Housing Survey (AHS) (51). We assigned water heating fuels probabilistically based on the space heating fuel and the location of the household. *SI Appendix* 1 outlines all data preprocessing steps.

Energy Use and GHG Model. We estimated total fuel and electricity demand for each household in 2015 using regression models derived from the US Energy Information Administration's 2015 Residential Energy Consumption Survey (RECS) (24). Input data were building-level attributes, county-level climate data (52), state-level fuel (53–55) and electricity (56) prices, and urban-rural status (8). We ran 10 Monte Carlo simulations to test the impacts of parameter uncertainty and probabilistic fuel assignment. *SI Appendix, Appendix 1: Methodological Details* details all data sources for the energy and GHG estimation and model.

To calculate space heating and water heating, we developed 10 models covering consumption of electricity, natural gas, fuel oil, liquid propane, and miscellaneous fuels (e.g., wood, coal). We developed two additional electricity models for space cooling and nonthermal uses (i.e., appliances and household electronics). The models were log-linear in form. *SI Appendix*, Tables SI-6–17 detail model coefficients and statistics. Relevant models were assigned based on each home's space and water heating fuels. We prioritized data from CoreLogic, substituting with data from the AHS as needed. The AHS counts homes using coal, propane, wood, solar, natural gas, electricity, or other fuels in each block group. Each model run probabilistically assigned space and water heating fuels to households as needed. This minimally affected aggregate model results (*SI Appendix*, Table SI-28).

We converted fuels to emission using EIA factors (57) and electricity to emissions (including line losses) with US Environmental Protection Agency eGrid data (34). We downsampled utility grids in Boston MSA and Los Angeles MSA to capture spatial variation in electrical grid coverage (58). GHG intensities for Los Angeles' electrical grids were from the UCLA Energy Atlas (20) and power disclosure labels, while Boston's grids were from power disclosure labels. *SI Appendix*, Table SI-20 shows the grids and carbon intensities. We excluded emissions from fuel extraction and refining, which are similar (8–11%) across the contiguous United States (16).

Results Analysis. The model estimated energy and GHGs for individual homes. We estimated energy intensity and GHG intensity for each state by dividing estimated energy used and GHGs emitted by total area in each state's sample. We estimated tons CO_2-equivalents per capita annually by dividing total GHGs for each ZIP code or block group by the 2015 population (8). To reduce underestimates, we excluded ZIP codes and block groups with missingness above 10%. We excluded small samples (<100 residents or <200 homes) to control for outliers, and we removed areas with m^2 per person in the bottom and top percentiles, as high and low values indicated unreliable population or area estimates. Our final subsample included 8,858 US ZIP codes (covering ∼60,000,000 households and half the US population), 3,079 block groups in Boston MSA, and 6,800 block groups in Los Angeles MSA. In the two MSAs, point data on CO_2 tons/cap are spatially interpolated using multilevel b-splines at 30-m spatial resolution (threshold error = 0.001) (59).

SUSTAINABILITY SCIENCE

The US Department of Housing and Urban Development's sets criteria for "low income," "very low income," and "extremely low income" households in every county of the US in 2015 according median household income and number of household members (30). We designated a ZIP code as low income if its median income falls below the "low income" threshold set for the average number of people per household in that ZIP code.

Scenarios. Four scenarios tested if grid decarbonization, energy retrofits, and distributed low-carbon energy systems could meet the Paris Agreement targets for existing US homes. The United States committed to 28% GHG reduction by 2025 and to 80% reduction by 2050 from 2005 levels (39). For residential energy, this translates to 2.64 t CO_2-e/cap in 2025 and 0.65 t CO_2-e/cap in 2050. Scenarios excluded emissions embodied in producing and installing the technologies needed to realize these transitions. Although it might become substantial by 2050, we also excluded electricity used to charge electric vehicles, which is attributed to the transport sector.

All scenarios account for projected decreases in heating-degree days and increases in cooling-degree days due to climate change. Climate change projections are based on Representative Concentration Pathway 4.5, which estimates a rise of 1.8 °C in global average temperature by 2100 (60). Differences in technology adoption rates, efficiencies and lifetimes, electrical grid intensities, and building insulation improvements in scenarios 1–3 are from the 2020 Annual Energy Outlook (40). Scenario 4 envisions increased penetration rates of high-efficiency household heating and cooling equipment, more aggressive retrofits to improve building insulation, and increased deployment of distributed low-carbon energy generation to meet the 2050 Paris Agreement. *SI Appendix* 1 provides additional details of the scenarios.

Scenario 1: Baseline. Electrical grids are decarbonized at the same rate as projected in the reference scenario of the 2020 Annual Energy Outlook. Space heating and cooling equipment and water heaters in each household are retired at rates consistent with the mean lifetime estimated by the EIA, such that the final market share of various technologies in the model align with Annual Energy Outlook 2050 projections. Installed equipment have the predicted average market efficiency for a given technology at the time of installation (61). Energy consumption calculated using the 12 regression models were adjusted using the appropriate efficiency factor from the literature. We assume electricity use by consumer electronics increase moderately (1.1% per year), but these are largely offset by more efficient lighting and home appliances. Increased adoption of air conditioning equipment into the US housing stock due to climate change was estimated using empirical relationships between projected cooling-degree days and air conditioning penetration in US cities (62). Building shells are retrofitted to meet International Energy Conservation Code (40) at a rate of 1.1% per year across the entire housing stock, producing a 30% reduction in heating demand and a 10% reduction in cooling load for pre-2015 homes using a 2015 baseline.

Scenario 2: Aggressive Energy Retrofits. This scenario highlights decarbonization through higher efficiency appliances and electronics. It is identical to scenario 1 except that when household heating or cooling equipment is retired, it is replaced with the best-in-class efficiency for that specific technology for the installation year. We also assumed that consumer electronics and households appliances achieve the higher efficiencies as projected in the Annual Energy Outlook, ultimately reducing electricity demand.

An aggressive energy retrofit program is adopted, whereby 60% of the building stock is upgraded between 2015 and 2050 (1.7% annual retrofit rate, compared to 1.1% in the Annual Energy Outlook), in line with similar deep retrofit scenarios in other building energy projections (e.g., BLUE Map, 3CSEP) (63, 64). Retrofitted homes reduce baseline heating load by 49% and cooling load by 25%, half of the optimal achievable savings from eliminating infiltration, improved insulation, and new windows according to US Department of Energy estimates (65), similar to observed savings in "deep" energy retrofits in the United States (66). Improving insulation and windows does not necessarily happen in tandem with upgrades to heating and/or cooling equipment. Performing deep energy retrofits in stages like this is less likely to meet owner resistance due to prolonged disruption, high upfront capital costs, and other challenges (66).

Scenario 3: Grid Decarbonization with Aggressive Energy Retrofits. This scenario examined whether decarbonizing the electrical grid can enable meeting the Paris 2050 goal. The electrical grid corresponds to the "$15 carbon dioxide allowance fee" scenario in the 2020 Annual Energy Outlook, which projects an ∼80% reduction in CO_2 intensity from electricity production compared to 2005 averaged across US grids. The reduction is due primarily to the conversion of coal to gas steam plants and marked increases in power from conventional hydroelectric, geothermal, biomass, solar, wind, and other low-carbon sources (5). All other aspects of the model are identical to scenario 2.

Scenario 4: Distributed Low-Carbon Energy. Background electric grids and the shell retrofit rate remain unchanged from scenario 3, but significant changes are made to the mix of heating and cooling technologies, and there is increased emphasis on distributed, low-carbon energy sources. The scenarios include a balanced portfolio of technologies and retains some conventional fossil fuel-based technologies, which is generally agreed upon as the most realistic future for the US energy and residential sectors (67).

This scenario assumed higher adoption rates of low-energy home heating and cooling equipment than the Annual Energy Outlook. Conventional furnaces were retired at higher rates, particularly gas- and oil-fed technologies, and replaced by ground source, electric, and gas-fired heat pumps of the highest available efficiency. Model allocation of new technologies is constrained by environmental conditions and housing characteristics. For instance, geothermal heat pumps were limited to single-family and semidetached homes, which are more likely to have adequate space for ground loops. Electric heat pumps are preferred over natural-gas heat pumps in regions of the United States with higher cooling loads, since the former are significantly more efficient at space cooling (61).

The scenario includes moderate deployment of distributed energy systems. For instance, the share of CHP supplying homes was doubled to ∼15% by 2050. Cogeneration plants relied on turbine-driven systems and reciprocating engines during the early years of the projection, but then switch to fuel cells, which provide a more balanced power-heat ratio, as the technology matures after 2030 (64). The fraction of carbon-free feedstock was increased from 10% in 2015 to 75% in 2050. These systems were constrained to medium- and high-density neighborhoods, where capital costs and distribution losses would be realistic. Two-fifths of homes were outfitted with either photovoltaics or solar water heaters, a moderate estimate for potential US solar coverage (45), with the latter concentrated in the Southwest United States, where solar insolation is highest. We do not explicitly model the proliferation of wind power, although it is implicit in EIA projections for the decarbonizing electricity grid.

Data Availability. The data and code that support the findings of this study are available on the Open Science Framework platform (DOI: 10.17605/OSF.IO/VH4YJ), with the exception of CoreLogic data, which are available for purchase from CoreLogic Inc. (https://www.corelogic.com/).

ACKNOWLEDGMENTS. We gratefully acknowledge the financial support of this work by the National Science Foundation through the Environmental Sustainability Program (Award 1805085). The authors are grateful to K. Arthur Endsley in helping us understand the CoreLogic data. Thanks to Nancy R. Gough for editorial assistance. We would also like to thank the Erb Institute for Global Sustainable Enterprise at the University of Michigan for their generous support of this work.

1. US Energy Information Administration, *Monthly energy review-September 2019*, (DOE/EIA-0035[2019/9], US Energy Information Administration, Washington, DC, 2019).
2. World Resources Institute, Historical emissions. CAIT Climate Data Explorer (2014). http://cait.wri.org. Accessed 2 October 2019.
3. US Census Bureau, 2017 National population projection tables. https://www.census.gov/programs-surveys/popproj.html. Accessed 30 September 2019.
4. National Research Council, "Driving and the built environment: The effects of compact development on motorized travel, energy use, and CO_2 emissions" (Special Report 298, The National Academies Press, 2009).
5. US Energy Information Administration, Annual energy outlook 2020. https://www.eia.gov/outlooks/aeo/. Accessed 1 April 2020.
6. I. Lima Azevedo, M. G. Morgan, K. Palmer, L. B. Lave, Reducing U.S. residential energy use and CO2 emissions: How much, how soon, and at what cost? *Environ. Sci. Technol.* **47**, 2502–2511 (2013).
7. W. Steffen *et al*., Trajectories of the earth system in the Anthropocene. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 8252–8259 (2018).
8. S. Manson, J. Schroeder, D. Van Riper, S. Ruggles, IPUMS National Historical Geographic Information System (Version 14.0, IPUMS, Minneapolis, MN, 2019). http://doi.org/10.18128/D050.V14.0. Accessed 4 October 2019.
9. E. Molina, "Housing development, planning, and the environment" in *Housing America: Issues and Debates*, (Routledge, ed. 1, 2017), pp. 135–176.
10. T. Suchan *et al*., "Population distribution" in *Census Atlas of the United States*, (US Census Bureau, 2007), pp. 8–27.

11. O. Lucon *et al*., “Buildings” in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, O. Edenhofer *et al*., Eds. (Cambridge University Press, 2014), pp. 671–738.
12. Di. Ürge-Vorsatz *et al*., Locking in positive climate responses in cities. *Nat. Clim. Chang.* **8**, 174–177 (2018).
13. K. C. Seto *et al*., Carbon lock-in: Types, causes, and policy implications. *Annu. Rev. Environ. Resour.* **41**, 425–452 (2016).
14. E. Kneebone, A. Berube, “Suburban poverty by the numbers” in *Confronting Suburban Poverty in America*, (Brookings Institution Press, 2013), pp. 13–36.
15. S. Pincetl, J. P. Newell, Why data for a political-industrial ecology of cities? *Geoforum* **85**, 381–391 (2017).
16. C. M. Jones, D. M. Kammen, Quantifying carbon footprint reduction opportunities for U.S. households and communities. *Environ. Sci. Technol.* **45**, 4088–4095 (2011).
17. D. J. Bednar, T. G. Reames, G. A. Keoleian, The intersection of energy and justice: Modeling the spatial, racial/ethnic and socioeconomic patterns of urban residential heating consumption and efficiency in Detroit, Michigan. *Energy Build.* **143**, 25–34 (2017).
18. C. Jones, D. M. Kammen, Spatial distribution of U.S. household carbon footprints reveals suburbanization undermines greenhouse gas benefits of urban population density. *Environ. Sci. Technol.* **48**, 895–902 (2014).
19. K. Song, S. Qu, M. Taiebat, S. Liang, M. Xu, Scale, distribution and variations of global greenhouse gas emissions driven by U.S. households. *Environ. Int.* **133**, 105137 (2019).
20. S. Pincetl e*t al*, UCLA energy atlas. https://energyatlas.ucla.edu/en/. Accessed 1 October 2019.
21. K. R. Gurney *et al*., Quantification of fossil fuel CO2 emissions on the building/street scale for a large U.S. city. *Environ. Sci. Technol.* **46**, 12194–12202 (2012).
22. K. Dol, M. Haffner, *Housing Statistics in the European Union in 2010*, (Ministry of the Interior and Kingdom Relations, The Hague, 2010).
23. M. Salari, R. J. Javid, Residential energy demand in the United States: Analysis using static and dynamic approaches. *Energy Pol.* **98**, 637–649 (2016).
24. US Energy Information Administration, Residential Energy Consumption Survey (RECS). https://www.eia.gov/consumption/residential/. Accessed 6 February 2019.
25. US Energy Information Administration, Use of energy explained–Energy use in homes. https://www.eia.gov/energyexplained/use-of-energy/homes.php. Accessed 7 November 2019.
26. US Energy Information Administration, "Annual energy outlook 2019 with projections to 2050" (US Department of Energy, Washington, DC, 2019).
27. J. Blanchard, E. Giever, S. Widder, M. Baechler, "Actual and estimated energy savings comparison for deep energy retrofits in the Pacific Northwest" (PNNL-21870, Pacific Northwest National Laboratory, Richland, WA, 2012).
28. US Energy Information Administration, “*What’s new in how we use energy at home: Results from EIA’s 2015 residential energy consumption survey*” (RECS, 2018).
29. US Energy Information Administration, Maine state energy profile. https://www.eia.gov/state/?sid=ME. Accessed 14 October 2019.
30. US Department of Housing and Urban Development, Income limits. https://www.huduser.gov/portal/datasets/il.html#2015. Accessed 18 September 2019.
31. J. Min, Z. Hausfather, Q. F. Lin, A high-resolution statistical model of residential energy end use characteristics for the United States. *J. Ind. Ecol.* **14**, 791–807 (2010).
32. K. C. Seto *et al*., “Human settlements, infrastructure, and spatial planning” in *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, O. Edenhofer, Ed. *et al*. (Cambridge University Press, 2014), pp. 923–1000.
33. B. Güneralp *et al*., Global scenarios of urban density and its impacts on building energy use through 2050. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 8945–8950 (2017).
34. US Environmental Protection Agency, eGrid summary tables. https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid. Accessed 14 May 2019.
35. United Nations Department of Economic and Social Affairs, "World urbanization prospects: The 2018 revisions" (ST/ESA/SER.A/420, United Nations, New York, 2019).
36. California Energy Commission, Utility annual power content labels for 2015. https://energyarchive.ca.gov/pcl/labels/2015_index.html. Accessed 14 October 2019.
37. C. Cerezo Davila, C. F. Reinhart, J. L. Bemis, Modeling Boston: A workflow for the efficient generation and maintenance of urban building energy models from existing geospatial datasets. *Energy* **117**, 237–250 (2016).
38. P. Hibbard, P. Darling, "Fuel mix and greenhouse gas emissions of municipal electric light plants in Massachusetts" (Analysis Group, Inc., Boston, MA, 2019).
39. United Nations Framework Convention on Climate Change, NDC registry (interim). https://www4.unfccc.int/sites/NDCStaging/Pages/All.aspx. Accessed 28 October 2019.
40. US Energy Information Administration, "*Assumptions to the annual energy outlook 2020: Residential demand module*" (US Department of Energy, Washington, DC, 2020)
41. US Energy Information Administration, "*Annual energy outlook 2020: Case descriptions*" (US Department of Energy, 2020).
42. IRENA, "Renewable energy in district heating and cooling: A sector roadmap for REmap" (International Renewable Energy Agency, 2017).
43. D. J. Bednar, T. G. Reames, Recognition of and response to energy poverty in the United States. *Nat. Energy*, 10.1038/s41560-020-0582-0 (2020).
44. B. Ástmarsson, P. A. Jensen, E. Maslesa, Sustainable renovation of residential buildings and the landlord/tenant dilemma. *Energy Pol.* **63**, 355–362 (2013).
45. B. Sigrin, M. Mooney, "Rooftop solar technical potential for low-to-moderate income households in the United States" (NREL/TP-6A20- 70901, National Renewable Energy Laboratory, Boulder, CO, 2018).
46. P. W. G. Newman, J. R. Kenworthy, Gasoline consumption and cities. *J. Am. Plann. Assoc.* **55**, 24–37 (1989).
47. Congressional Research Services, "The regional greenhouse gas initiative: Background impacts, and selected issues" (R41836, Congressional Research Service, Washington, DC, 2019).
48. S. Nadel, “Energy savings, Consumer economics, and greenhouse gas emissions reductions from replacing oil and propane furnaces, boilers, and water heaters with air-source heat pumps” (Rep. A1803, American Council for an Energy-Efficient Economy, 2018).
49. T. L. Daniels, The use of green belts to control sprawl in the United States. *Plann. Pract. Res.* **25**, 255–271 (2010).
50. CoreLogic, CoreLogic. https://www.corelogic.com. Accessed 3 October 2019.
51. US Census Bureau, American Housing Survey (AHS). https://www.census.gov/programs-surveys/ahs.html. Accessed 19 May 2019.
52. National Oceanic and Atmospheric Administration, Data from "U.S. Climate Divisions." nClimDiv Dataset. https://www.ncdc.noaa.gov/monitoring-references/maps/us-climate-divisions.php#grdd. Accessed 14 May 2019.
53. US Energy Information Administration, Residential heating oil weekly heating oil and propane prices (October–March). https://www.eia.gov/dnav/pet/pet_pri_wfr_a_EPD2F_PRS_dpgal_w.htm. Accessed 15 May 2019.
54. US Energy Information Administration, Residential propane weekly heating oil and propane prices (October–March). https://www.eia.gov/dnav/pet/pet_pri_wfr_a_EPLLPA_PRS_dpgal_w.htm. Accessed 15 May 2019.
55. US Energy Information Administration, Natural gas prices. https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PRS_DMcf_m.htm. Accessed 15 May 2019.
56. US Energy Information Administration, Electricity. https://www.eia.gov/electricity/data.php#sales. Accessed 15 May 2019.
57. US Energy Information Administration, Carbon dioxide emissions coefficients. https://www.eia.gov/environment/emissions/co2_vol_mass.php. Accessed 14 May 2019.
58. A. J. Fang, J. P. Newell, J. J. Cousins, The energy and emissions footprint of water supply for Southern California. *Environ. Res. Lett.* **10**, 114002 (2015).
59. S. Lee, G. Wolberg, S. Y. Shin, Scattered data interpolation with multilevel b-splines. *IEEE Trans. Vis. Comput. Graph.* **3**, 228–244 (1997).
60. R. H. Moss *et al*., The next generation of scenarios for climate change research and assessment. *Nature* **463**, 747–756 (2010).
61. Navigant Consulting Inc., "*EIA-Technology forecast updates–Residential and commercial building technologies–Reference case*" (US Department of Energy, 2018).
62. D. J. Sailor, A. A. Pavlova, Air conditioning market saturation and long-term response of residential cooling energy demand to climate change. *Energy* **28**, 941–951 (2003).
63. D. Ürge-Vorsatz *et al*., "Best practice policies for low energy and carbon buildings: A scenario analysis. Research report prepared by the Center for Climate Change and Sustainable Policy (3CSEP)" (Global Buildings Performance Network, Paris, France, 2012).
64. P. Diczfalusy, B. Taylor, "Technology roadmap, energy-efficient buildings: Heating and cooling equipment" (International Energy Agency, Paris, France, 2011).
65. US Department of Energy, “Increasing efficiency of building systems and technologies” in *Quadrennial Technology Review. An Assessment of Energy Technologies and Research Opportunities*, (Department of Energy, 2015), pp. 145–182.
66. B. Less, I. Walker, "A meta-analysis of single-family deep energy retrofit performance in the U.S" (Lawrence Berkeley National Laboratory, Berkeley, CA, 2014).
67. C. T. M. Clack *et al*., Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 6722–6727 (2017).